Beagle 2 Simulation and Calibration for Ground Segment Operations

Barnes, Dave; Phillips, Nigel ; Paar, Gerhard

Publication date:
2003

Beagle2 Simulation and Calibration for Ground Segment Operations

Dave Barnes,
Department of Computer Science,
University of Wales, Aberystwyth,
SY23 3DB, UK.
dpb@aber.ac.uk

Nigel Phillips,
Astrium Ltd.,
Stevenage,
SG1 2AS, UK.
nigel.phillips@astrium-space.com

Gerhard Paar,
Institute of Digital Image Processing,
Joanneum Research, Graz,
A-8010, Austria.
gerhard.paar@joanneum.at

Keywords Beagle2, calibration, kinematics, simulation, DEM generation.

Abstract

Beagle2 [1] as part of the ESA Mars Express mission [2] will be launched in May 2003. The primary science goal of Beagle2 is to search for the presence of life on the planet with the aid of a sophisticated package of scientific instruments [3]. These include mass, Mössbauer and X-ray spectrometers, a microscope, stereo camera system (SCS), and environment sensors. All but the mass spectrometer (Gas Analysis Package - GAP) are mounted on a structure called the PAW, which also carries a mole device (PLUTO) to obtain sub-surface, and/or under rock samples, and a corer/grinder to remove weather rind from rock surfaces. Deployment of the PAW is achieved using a robot ARM that has been designed and built by Astrium Ltd [4, 5]. The operation of the ARM with its PAW 'end- effector' is therefore of paramount importance during the mission, and considerable effort has been expended to validate its performance, and to provide ARM software tools that can be used during mission operations. The work has involved the creation of a virtual Beagle2 software simulation, kinematics calibration, and subsequent PAW SCS calibration, and Beagle2 environment DEM generation. This paper provides details our work in these areas, together with the results that we have obtained when using our calibrated Beagle2 simulation to generate ARM joint angle data which have then been used to command the real Beagle2 ARM.

1. Background

The Space Robotics Group at Aberystwyth group have received Beagle2 ARM, PAW and lander base and lid CAD data from Astrium and the Space Research Centre (SRC), Leicester. This has been imported into a robot simulation software package, ENVISION(TR) [6], to create a virtual Beagle2. The strategy is to use this virtual Beagle2 during the mission so that engineers and scientists can validate, and plan the operation of Beagle2 on Mars, before commanding the real Beagle2 ARM to move. The stereo cameras mounted on the PAW will capture images of the Martian terrain, and software developed by Joanneum Research, Austria, is able to convert this data into a 3D terrain digital elevation model (DEM). When in this format, Martian terrain information can be imported into the Beagle2 virtual model, which will allow the scientists and engineers to be able to 'fly' around the Beagle2 virtual environment and visualise rocks and the Martian surface, in their search for the best science targets. Once these have been selected, the virtual Beagle2 can be used to ensure that the targets can be reached by the ARM and PAW, and that no part of the ARM and PAW will collide with neighbouring rocks, or any other part of the Beagle2 lander. For the virtual Beagle2 model to be used in this way, the software model must be calibrated with the real Beagle2, so that the virtual and real ARM kinematics are identical. The Aberystwyth group has completed the generation of the virtual Beagle2 model, and the necessary kinematics calibration. The stereo cameras have been calibrated relative to the ARM and PAW, thus enabling camera images to be obtained, and DEM data generated for importing into the virtual Beagle2 environment.

This paper provides details of our four areas of work namely, the virtual Beagle2 software simulation, kinematics calibration, Beagle2 environment DEM generation, and calibration tests for ground segment operations.

2. Virtual Beagle2 Simulation

Envision(TR) is a mature robot simulation software product that has a long industrial track record and exposure to demanding robotic applications. The software is able to import Catia CAD part data, which is an essential capability, and allows Astrium and Leicester designed Beagle2 parts to be imported into the simulation environment without any modification to that data. Once within the Envision(TR) software environment, the parts can be 'assembled' into a virtual Beagle2, complete with lander base, lid, robot ARM and instrument PAW. Hence given that the Beagle2 parts have been machined as per

Arm's DH Parameters

	Theta: R(z)	d: T(z)	a: T(x)	Alpha: R(x)	Beta: R(y)
Joint 1	-126.947	0.000 mm	134.260 mm	0.000 deg	0.000 deg
Joint 2	-173.053 deg	-28.579 mm	1.182e-005 mm	90.000 deg	0.000 deg
Joint 3	0.011 deg	-22.800 mm	378.300 mm	0.000 deg	0.000 deg
Joint 4	179.988 deg	0.999 mm	330.900 mm	0.000 deg	0.000 deg
Joint 5	0.000 deg	85.371 mm	9.487e-006 mm	90.000 deg	0.000 deg

OK Cancel

Figure 1: Beagle2 ARM Denavit-Hartenberg parameters.

their Catia design, the virtual Beagle2 is geometrically identical to the real Beagle2 (within manufacturing tolerances). Once assembled, a kinematics model for the robot ARM and other moving Beagle2 parts can be created. The conventional robotics Denavit-Hartenberg (D-H) method [7] has been used to define the parameters required for deriving the forward and inverse kinematics model for the Beagle2 ARM. D-H parameters for the uncalibrated Envision(TR) ARM model are shown in figure 1.

Texture maps and VRML data can be imported into the virtual Beagle2 simulation, thus allowing Martian panoramic camera images, Wide Angle Mirror (WAM) images, and Martian DEM terrain data to be visualised within the same virtual Beagle2 environment, see figure 2. Using this Beagle2 model we can mount a virtual camera on the virtual PAW SCS (or elsewhere), and obtain a virtual pre-view of the subject(s) that are to be investigated using the real SCS. The resolved motion capability of the ARM (inverse kinematics), allows automatic ARM configuration(s) generation, automatic ARM/PAW working envelope generation, joint-by-joint motion for mission planning and operations, and ARM joint data readout ready for conversion to ARM potentiometer values prior to their transmission to Beagle2 on Mars. ARM/PAW/Lander/DEM collision detection can be performed, and Envision(TR)'s Graphical Simulation Language allows mission scripting and rehearsal. User definable lighting (e.g. Sun position), and resultant shadowing on the ground is possible together with a user definable Envision(TR) GUI for Lander Operations Control Centre (LOCC), and Lander Operations Planning Centre (LOPC) activities.

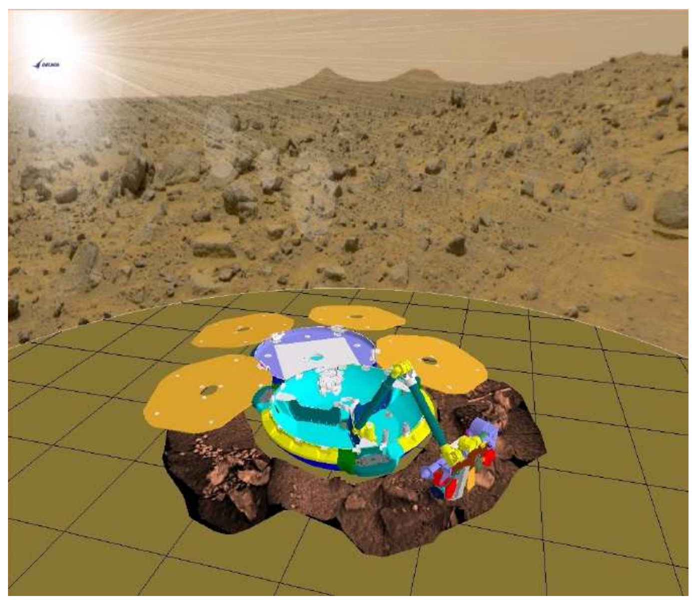

Figure 2: Beagle2 simulated in Envision(TR) with imported panoramic camera image backdrop (image courtesy of NASA/JPL), and terrain DEM.

3. Beagle2 Kinematics Calibration

Once the virtual Beagle2 simulation had been created, this model required calibration with the real Beagle2 so that it can be used for mission planning purposes. The Beagle2 simulation can generate the robot ARM joint values for a desired configuration and position in Beagle2 Cartesian space. These joint values will then be uploaded to the real Beagle2 on Mars. Hence the kinematics of the virtual and real Beagle2 ARM must be identical. Our calibration measurement system included a Vicon 512 infra-red camera motion capture system [8], and a 1 *arcsecond* theodolite. During calibration, the real ARM was moved to a number of positions and orientations within its operating envelope, and these were measured using our Vicon measurement system. The key regions for calibration are the GAP (Gas Analysis Package) Inlet Port, the lander base calibration target, and the DEM terrain region (see section: Calibrated Beagle2 DM and FM ARM Tests). Prior to calibrating the virtual Beagle2 model, ARM joint potentiometer/angle validation tests, and ARM/PAW repeatability tests were undertaken using the Vicon measurement system.

For real/virtual ARM calibration, real joint angle and Vicon data were imported into the Envision(TR) environment. A Levenberg-Marquardt [9] nonlinear least squares fit was performed between the Vicon data and the virtual ARM when commanded to move to the same positions and orientations as the real ARM. This resulted in the modification of the virtual ARM joint-offsets so that its kinematics matched those of the real ARM. Figure 3 shows the calibration setup. Two of our seven Vicon cameras are shown in the background. The 1/3rd mass PAW is a rapid prototyped volumetrically identical PAW with a mass equal to that of the real PAW on Mars. Hence ARM defections comparable with those that will be experienced on Mars were produced. Figure 4 shows the Flight Model (FM) ARM calibration setup. The reflective spherical markers used by the Vicon system can be seen, and these were mounted coaxial with each PAW instrument. The group of three reflective markers that can be seen in figure 4 were used to reference the ARM (attached to its base mounting plate) to the Vicon 'L-Frame'. This L-Frame defined our calibration origin, and can be seen to the right of the ARM in figure 3. The base plate markers to L-Frame measurements were obtained using the theodolite. For the FM calibration work, the ARM links, base plate, and clean room floor were covered with low-reflecting materials to prevent stray reflections from ceiling lights etc. affecting the Vicon cameras. For the Development Model (DM) work we simply turned the lights out - which was not an option in a busy clean room! The 1/3rd mass PAW was bagged to prevent any residual dust (produced by the rapid prototyping process) from entering the clean room.

Due to the excellent correspondence between the as-designed/as-manufactured/as-imported into Envision(TR) ARM part geometric parameters (a tessellation SAG value of $0.02mm$ was used for the Envision(TR) part import process), the original D-H parameters of the Beagle2 ARM were retained during the calibration process. Rather the original ARM joint offsets were modified. Prior to calibration, the joint offset for each of the 5 joints was set to 0.00 *degrees*. The result of the joint offset calibration can be seen in figure 5. Calibration of Joint 1 required the largest joint offset angle correction. The joints are numbered: Joint 1 - ARM Body, Joint 2 - ARM Shoulder, Joint 3- ARM Elbow, Joint 4 - ARM Wrist Upper, and Joint 5 - ARM Wrist Lower. The next stage in the calibration process was to calibrate the PAW SCS, and undertake a number of theodolite measurements of the PAW so that it can be referenced to the calibrated Envision(TR) virtual ARM/PAW model during mission operations.

4. PAW SCS Calibration and Beagle2 Environment DEM Generation

Prior to environment DEM generation, the PAW stereo camera system (SCS) required calibration. The first stage included an internal camera calibration to determine lens distortion, interior orientation and relative orientation between the cameras. Camera image data of a SCS camera calibration target was obtained for this operation. Figure 3, to the left of the ARM, shows the top of this calibration rig. This first stage was performed initially using the 1/3rd mass PAW which was fitted with COTS cameras. This allowed the SCS internal camera calibration process to be rehearsed and refined using the DM setup, prior to performing the process on the final FM PAW SCS under clean room conditions.

The second camera calibration stage involved the determination of a 'Zero PAW State' whereby the relationship between SCS and the ARM was noted. This state is a nominal position outside of the lander base that has the SCS pointing down towards the terrain region, see figure 6. The Zero PAW State will be a position that the ARM will be commanded to move to during Martian terrain SCS image collection. A Zero PAW State was determined both for the DM and FM ARMs. A Helmert Transform will be used to generate a Cartesian vector and rotation matrix between any image data obtained from the SCS, when on Mars, and Zero PAW State, thus allowing the position and orientation correspondence between a SCS image and the Envision(TR) virtual ARM to be calculated. 6 fixed points on the PAW were chosen (e.g. a sharp corner of an instrument), and with the DM ARM positioned in the Zero PAW State, the Cartesian position of each PAW point was calculated from measurement data obtained using the theodolite. The position

Figure 3: Calibration setup with the Beagle2 Development Model (DM) ARM, 1/3rd mass PAW, and mock terrain.

Figure 4: Calibration setup with the Beagle2 Flight Model (FM) ARM and 1/3rd mass PAW in Astrium Ltd. clean room.

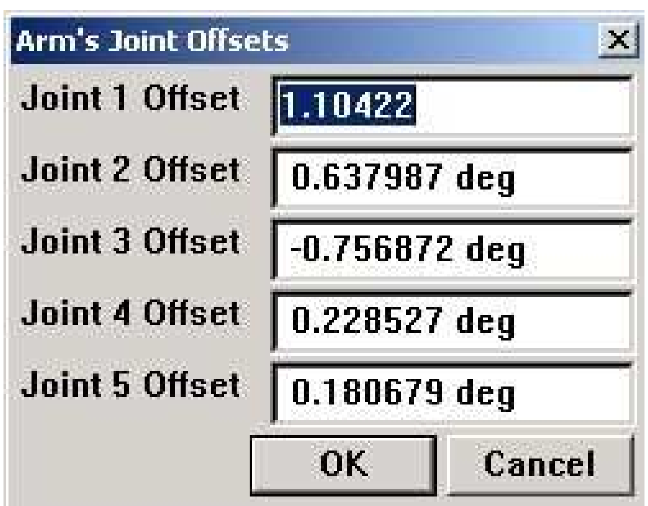

Figure 5: Beagle2 ARM joint offsets after calibration.

Figure 6: Beagle2 FM ARM and 1/3rd mass PAW in Zero PAW State position.

of each point was calculated relative to a local coordinate frame origin. During FM PAW SCS calibration, the PAW was not attached to any Beagle2 ARM. The process took place at a different geographic site (SRC, Leicester). During FM PAW SCS calibration, the same 6 fixed PAW points were measured, but this time relative to a different local coordinate origin. Given this information, any image gathered by the SCS (where ever it may be) can be transformed with the aid of a Helmert transform from one coordinate frame to another. When on Mars, as the ARM is moved, then so will the 6 PAW points move, and the Envision(TR) calibrated ARM/PAW model can be interrogated to determine the new virtual PAW point positions. Using a Helmert transform once more, will enable a gathered SCS image to be transformed to its correct 'on Mars' position, relative to the FM ARM Zero PAW State.

To generate a terrain DEM, the terrain under investigation is imaged by moving the ARM with attached PAW SCS over the terrain surface at a height determined by the cameras' focusing range. The combination of a statistical based hierarchical feature vector matching method, and Helmert Transforms on the stereo image data, allows a DEM mosaic to be generated. The resultant DEM can be rendered with the captured camera ortho RGB images and exported as a VRML file. Once in this format, the DEM and ortho RGB texture map can be imported into the virtual Beagle2 Envision(TR) environment. Figure 7 shows an Envision(TR) screen dump. The calibrated ARM and PAW are shown together with an imported mock terrain DEM. This was generated from camera data gathered by moving the ARM and 1/3rd mass PAW during the DM calibration work. The mock terrain shown in figure 3 was used. Figure 8 shows the same DEM, but this time it has been rendered with the ortho RBG texture obtained from the camera images. Note the white (no data) regions in figure 8, which is due to terrain occlusion. This could have been remedied by obtaining further images at different SCS positions and orientations.

5. Calibrated Beagle2 DM and FM ARM Tests

There are three key regions within the Beagle2 work envelope that the ARM must be able to move to, and it must be able to position the PAW and selected instrument with both an accuracy and repeatability of the order of $\pm 5mm$. These key regions are:

1. the *DEM terrain region* where sites of scientific interest will be examined by the PAW instruments,
2. the *calibration target* (used by the PAW instruments for measurement calibration), and
3. the *GAP (Gas Analysis Package) inlet port* (Martian soil samples collected by PLUTO will be deposited within the GAP inlet port for analysis by the mass spectrometer).

During the calibration process, considerably more Vicon measurements were taken in these key regions, than elsewhere within the ARM's work envelope. Figure 9 shows results from the ARM repeatability studies when operating in the DEM terrain region.

The ARM was moved to a number of different start positions, and from each of these start positions, the ARM was commanded to move to the same goal position in the DEM terrain region. Vicon measurements were taken of the ARM after it had reached the goal position. Figure 9 shows the Vicon data, and each measured goal position is represented as a small sphere of diameter $0.1mm$. A bounding sphere was created such that all the smaller spheres resided within its volume. This larger sphere represents a repeatability volume, and is shown in figure 9 as a circle of diameter $\approx 8mm$. It was observed that due to the ARM's proportional control, there was always a small overshoot on each joint (typically $\approx 0.1 degree$), also joints 4 and 5 suffer from backlash due to the bevel gears in their drive train (joints 1 - 3 employ a direct drive from their harmonic gearboxes). Due to this overshoot and backlash, when the ARM joint potentiometers were interrogated, it was observed that the ARM was not exactly at the joint values that had been used to command the ARM to move to the goal position. To overcome this, the ARM was re-commanded to move once more to the same goal position. Whilst this manoeuvre could not overcome the overshoot (which is very predictable), it did serve to remove the backlash on joints 4 and 5. The resultant effect was a considerable improvement in the ARM's repeatability. Figure 9 shows a small group of spheres to the top right of the circle. These spheres were constructed from Vicon measurements taken at this re-commanded goal position. The locus diameter for this group of spheres was measured to be $\approx 0.6mm$, well within the desired repeatability of $\pm 5mm$. The repeatability study was performed for the GAP inlet port, and calibration target regions, and the same re-commanded goal position repeatability improvement was observed. Repeatability without re-commanding the ARM to move to the GAP inlet port and calibration target goal positions was measured to be $\pm 1mm$ in both cases.

5.1 DEM Terrain Region Accuracy

After we had conducted the ARM repeatability studies, virtual/real ARM accuracy investigations were conducted once a terrain DEM had been obtained. As part of our DM calibration work, SCS images of a mock Martian terrain were obtained by commanding the real ARM to move over the terrain. This data was processed to generate a terrain DEM, which was then imported into the virtual Beagle2 environment. The virtual Beagle2 PAW instruments were moved in turn to a location on the DEM surface, virtual ARM joint values were obtained for

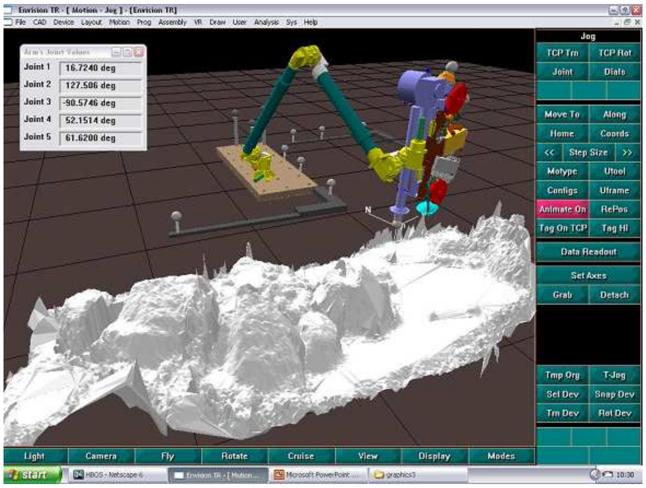

Figure 7: Envision(TR) screen dump showing calibrated Beagle2 ARM and PAW, plus imported mock terrain DEM (ortho RGB texture map not shown).

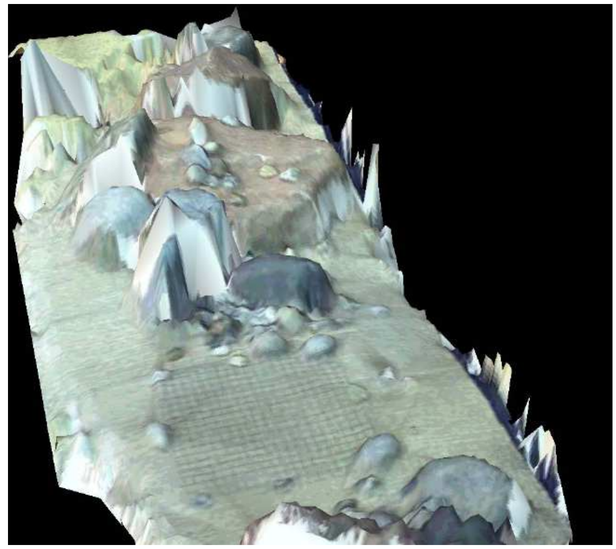

Figure 8: Imported terrain DEM plus ortho RGB texture map. The mock terrain rocks and pebbles can be seen clearly, together with a $1cm$ grid in the foreground.

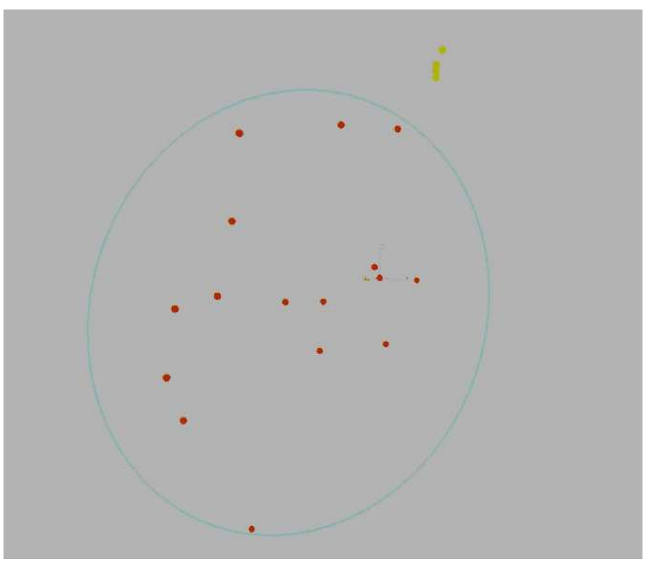

Figure 9: Real ARM/PAW repeatability results when commanded to a location within the DEM terrain region. The large circle has a diameter $\approx 8mm$. Each of the small spheres has a diameter $= 0.1mm$. Note the group of spheres (coloured yellow) to the top right of the circle - group locus diameter $\approx 0.6mm$.

Figure 10: DM ARM and 1/3rd mass PAW tests using virtual ARM/PAW model, and mock terrain.

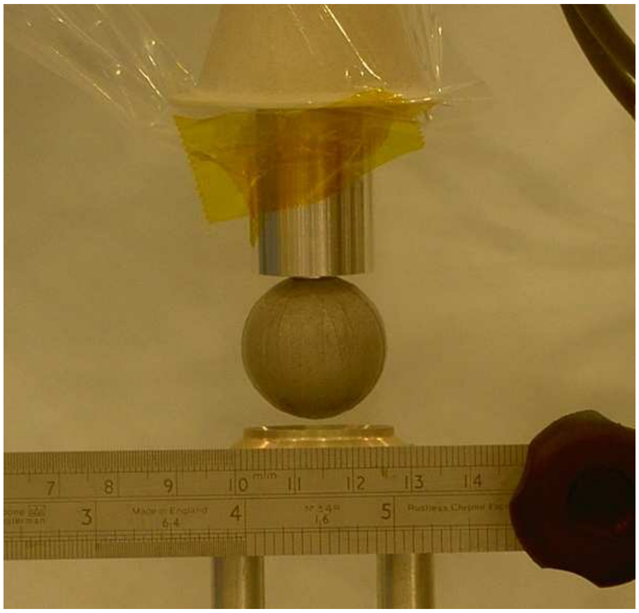

Figure 11: Mole/GAP Inlet Port error in L-Frame x dimension: $\approx +1mm$

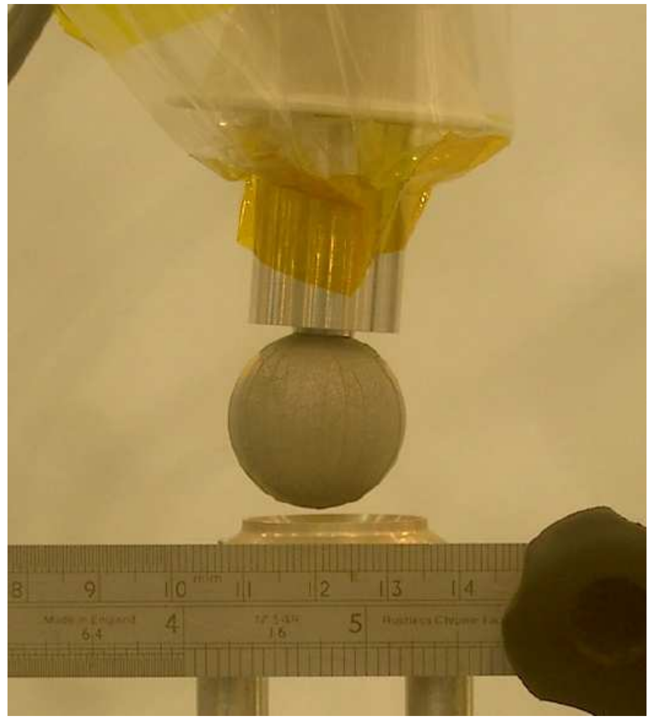

Figure 12: Mole/GAP Inlet Port error in L-Frame y dimension: $\approx -2mm$

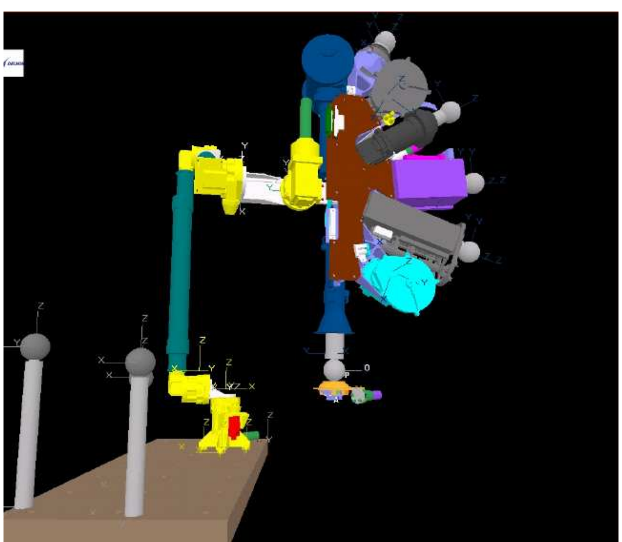

Figure 13: Calibrated Envision(TR) model with ARM and PAW positioned with the mole Vicon marker directly above and level with the the GAP inlet port.

Figure 14: FM ARM and 1/3rd mass PAW shown after being commanded to position the mole in the GAP inlet port using Envision(TR) generated ARM joint data.

each PAW configuration, and this data was input into the real ARM command interface. The motion of the real ARM was then observed, and measured, to compare virtual and real instrument end position and orientation, see figure 10. Typical absolute accuracy figures obtained in the x, y, and z axes were $+6mm$, $-1mm$, and $-5mm$, respectively, from the desired real DEM terrain region target position.

5.2 Calibration Target Accuracy

A similar test was performed using the calibrated Envision(TR) to obtain joint values for commanding the FM ARM to position an instrument's (e.g. X-ray spectrometer) Vicon marker against the calibration target plate. A representative calibration target plate was fixed to the ARM base plate in exactly the same position that it will occupy in the lander base. This plate can be seen towards the bottom of figure 14. Typical absolute accuracy figures obtained in the x, y, and z axes were $+6mm$, $+1mm$, and $+1mm$, respectively, from the desired calibration target position.

5.3 GAP Inlet Port Accuracy

Figure 13 shows the Envision(TR) model with the mole Vicon marker positioned directly above, and level with the GAP inlet port. Envision(TR) was interrogated to obtain the virtual ARM joint values for this position. These values were input to the real ARM command interface, and the real ARM was observed to move to this position. Typical absolute accuracy figures obtained in the x, y, and z axes were $+1mm$, $-2mm$, and $-1mm$, respectively, from the desired GAP inlet port target position. See figures 11, and 12. Encouraged by this finding, we removed the Vicon marker from the mole on the 1/3rd mass PAW, updated the virtual model accordingly, and obtained new Envision(TR) generated joint values for a position with the mole inserted into the GAP inlet port. These joint values were then input into the FM ARM command interface, and the motion of the real ARM was observed. Figure 14 shows the outcome of this motion. The mole was successfully inserted into the GAP inlet port using ARM joint data obtained from our calibrated Envision(TR) Beagle2 model. To conduct this test, a duplicate GAP inlet port was fixed to the ARM base plate in exactly the same position that it occupies in the lander base. This can be seen in figure 14.

6. Conclusion

We have successfully created a virtual Beagle2 model using the Envision(TR) software simulation package. This model has been calibrated with both the DM and FM ARMs, and we have rehearsed the process of generating a terrain DEM using the PAW SCS, real ARM and Envision(TR) software. We believe we are now in a position to generate joint values for commanding the FM ARM on Mars. A great deal has been learnt regarding how the DM and FM ARMs perform. We were surprised to learn that re-sending the same joint angle values to an ARM results in a significant improvement in repeatability ($\pm 4mm$ down to $\pm 0.3mm$!). ARM repeatability is most important during mission operations when the ARM is operating within the Martian terrain region. The PAW will be positioned against a Martian rock, and the corer/grinder will remove weather rind. The PAW instruments in turn will be positioned repeatedly against the area of cleaned rock surface. A force sensor on the wrist of the PAW will be used to detect rock contact. ARM accuracy becomes more important when the PAW instruments are being positioned against the calibration target plate. Damien Hirst has produced a spot painting on this plate. These spots have a diameter of $\approx 10mm$, and contain a variety of chemical pigments that will be used to calibrate the PAW instruments when on Mars. The measured ARM accuracy for the calibration target was found to be well within the limits demanded by the diameter of the spots. Accuracy is even more important when it comes to the GAP inlet port. The mole PLUTO will be used to obtain a Martian soil sample. Once PLUTO is retracted into the PAW, the sample capture part of PLUTO must be placed within the GAP inlet port. A sample handling mechanism will then allow the soil sample to be removed from PLUTO and placed within the mass spectrometer. The measured ARM accuracy for the GAP inlet port was found to be well within the limits demanded by the dimensions of the inlet port orifice. The DM ARM will be used during the mission as our Ground Test Model (GTM) at the LOCC. Thus allowing us to validate our virtual Beagle2 generated joint angle values, prior to their transmission to the FM ARM on Mars.

7. References

[1] See web page - http://beagle2.open.ac.uk/.

[2] See web page - http://sci.esa.int/home/marsexpress/.

[3] A. Brack. The exobiology exploration of Mars: a survey of European approaches. *Planetary and Space Science*, 48:1023–1026, 2000.

[4] N. Phillips. Robotic arm for Beagle2 Mars lander. In *Proceedings 6th ESA Workshop on Advanced Space Technologies for Robotics and Automation, ASTRA 2000, ESTEC NL*, December 2000.

[5] N. Phillips. Testing of the Beagle2 Instrument Arm. In *Proceedings 7th ESA Workshop on Advanced Space Technologies for Robotics and Automation, ASTRA 2002, ESTEC NL*, November 2002.

[6] See web page - http://www.deneb.com/products/envision.html.

[7] Denavit J. and Hartenberg R. A kinematic notation for lower pair mechanisms based upon matrices. *J. Applied Mechanics*, 1955.

[8] See web page - http://www.oxfordmetrics.co.uk/.

[9] Moré J.J. The Levenberg-Marquardt algorithm: Implementation and theory. In Watson G.A., editor, *Numerical Analysis*, number 630 in Lecture Notes in Mathematics, pages 105–116. Springer Verlag, 1977.